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Some Problems of Estimation of Synergism Effect in Multistress Life Models of Insulation Systems

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This paper contains an analysis of selected problems connected with to the phenomena of ageing of insulation systems exposed to various stresses. The main idea of the interaction - so called synergism, of ageing stresses in the phenomena of degradation of the insulation systems has been discussed and selected. Evaluations of the effect of synergism on the durability of insulation of electrical devices as well as recommendations of the pertinent standards for procedures of accelerated ageing testing are presented. An analysis of selected life models of insulation systems containing components describing of the synergism of stresses are included.

Key words : multistress (multifactor) ageing, interactions, synergism, life time, modelling

絶縁システムの複合劣化寿命に対する相乗効果検討の問題点

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この論文は、各種のストレスに曝された絶縁システムの劣化現象に関するある種の問題点についての分析結果について述べている。今まで、主として絶縁システムの劣化現象における各種ストレスの相互作用を所謂相乗作用として検討されてきたが、この論文では、電気装置の絶縁の耐用性に対する相乗効果の評価のみならず、加速劣化試験方法の適切な推奨基準についても述べている。また、部分要素をも含んだある種の絶縁システムに対するストレスの相乗効果に関する解析についても、記述している。

1. THE GENERAL EFFECTS OF THE INTERACTION OF AGEING STRESSES IN INSULATION - SYNERGISM

The synergism of the stresses and its evaluation, in view of the increasing number of ageing stresses, intensifying as a rule of the ageing effects in electrical devices, has been an object of interest not only of technical sciences for the purpose of adequate modelling of the durability of insulation systems, but also of social sciences - interesting modern direction, as it has been demonstrated in some monograph studies [ex.1]. Evaluation of the effects of intensified destructive action of simultaneously operating stresses remains the field of current interest of many researchers, both what regards the physical justification of the notations of the life models as well as what regards the proper planning of the ageing experiments.

The definition of interaction, the synonim of synergism, is given after [2, page 23].. -..."when the ageing effects produced by the factors of influence differ from the sum of the ageing effects produced by each factor in isolation, then interactive ageing is said to take place. The cause of the departure from combination of the separate ageing effects shall be called "interaction"......and the condition recommended for proper selection of the investigation method "..Knowledge of the actual physical mechanisms of insulation deterioration is important to a good and rational design of functional tests...." [2, page 13].

There are not too much of examples of theoretical justification for introduction of synergism to the life models of insulations. But any recapitulation can be found, for example, in monograph of Dmitrijevski and Wasilenko [3,4].

When justifying the use of a thermofluctuation life model of polymer insulation, Wasilenko [4] presents an interesting visualization of the evaluation of the probability of breaking up the molecules bond or/and the thermofluctuation recombination with and without the cooperating external stress - Fig.1. According to this theory, the external force does not induce the direct breaking-up of the bond, but, due to the expansion of the distance between the atoms and reduction of the potential energy of the barrier it favours the breaking-up of the bond under the influence of the fluctuation of heat energy.

If, in the insulation system there occurs an additional, external stress **P**, acting in the direction of the reaction path, e.g. mechanical tension, then the activation energy will be reduced by the value of the energy α **P**, performed above the system. If the process is to consist in the transfer of the particle from the the position **A** to the position **C**, when the particle **A** must suppress the energy barrier $\mathbf{W= E_B-E_A}$, necessary to pass through the point **B**. If there is no external stress, such a transfer is possible only as a result of incidental thermal fluctuation with energy equal at least to **W**. The probability **q(W)** of the occurence of such a fluctuation is very small. At the temperature **T**, the equilibrium state will become established in the system, the number of the broken bonds will be equal to the number of the recombinations since the probabilities of reactions with the directions **A→B→C** and **C→B→A** are indentical. On the other hand, if the external stress acts in the direction of reaction path, the energy barrier for the direction **A→B→C** will be diminished by α **P**, and for the opposite direction it will appropriately increase.

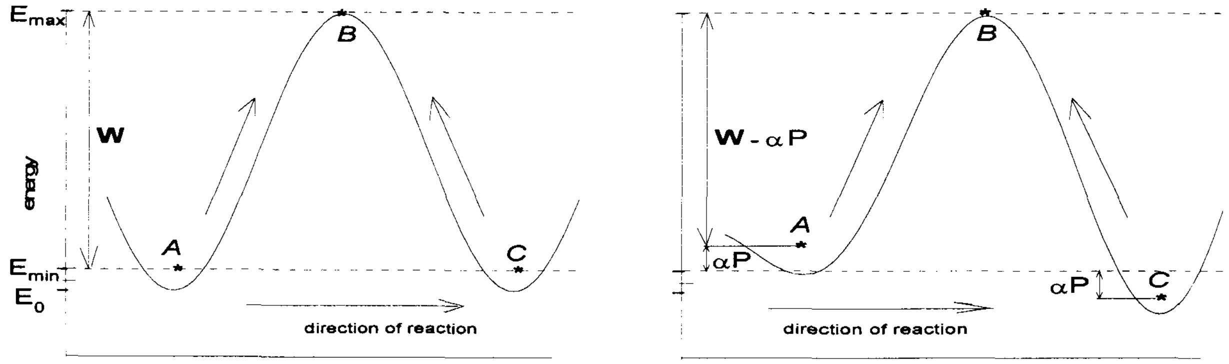

Fig.1 : The model of action of process with energetic barrier **W** under and without external stress **P**

Reduction of the potential barrier by the increasing external stress implies that thermal fluctuation of smaller energy will suffice to activate a particle, and the time of waiting for its occurence will be shorter.

When describing the multifactor stress of insulation, Dmitijevski [4] starts from the value of the energy **W(r)** of the interaction between the molecules:

$$W(r) = D\left[e^{-\frac{2(r-R)}{a}} - 2e^{-\frac{(r-R)}{a}}\right] \qquad (1)$$

where: D -dissociation energy of the bond,
r -distance between the molecules,
R -equilibrium distance between the molecules,
a -material constant.

After applying the external force P the energy barrier will be reduced by the value:

$$\Delta W = W'(r_2) - W(r_1) \qquad (2)$$

where: $W(r_1)$ -minimum energy at the distance r_1 between molecules; without the external stress P,
$W'(r_2)$ -extreme potential energy, at the distance r_2 between the molecules, occuring after application of such an external stress P.

If, for the stress P a dimensionless degradating factor "x" is introduced in the form:

$$x = \frac{aP}{D} \qquad (3)$$

and the energy required to break up the bond is denoted by:

$$\Delta W = D\,\varphi(x) \qquad (4)$$

where: ϕ (x)-the stress function;

then the life time of insulation can be in general described in a simplified form as:

$$t = \frac{1}{\tau_o} e^{\frac{D\varphi(x)}{2kT}} \qquad (5)$$

where: t -durability (life, endurance) of insulation,
k -Boltzmann constant,
T -absolute temperature,
τ_o -frequency of free vibration

Dmitijevski introduces considerable simplifications to derive the final analytical relations describing the life time. From among these the greatest doubts may be raised with respect to the following: neglecting the changes in the material properties during of ageing, assuming that insulation forms a series reliability model without allowing for the possibility of regeneration after breakdown at a weak point, neglecting of recombination processes.

Below there will be presented some of the consequences of adopting such a model of degradation, with the indication of the material constants adopted in the calculations by the above author.

According to the assumptions and denotations [4] given above, it can be assumed that for a thermal-electrical-mechanical stresses for a solid state insulation there has been introduced:

$$x = \frac{1}{D}\sqrt{(A e^{-bT}\beta\eta E)^2 \pm \gamma^2\sigma^2} \tag{6}$$

where: E -averaged electrical gradient between electrodes [V/m],

σ -average mechanical stress (described by the force [Newton]),

γ -size of insulation per one stressed bond of the basic structure of material (linear dimension [m])

β -the coefficient of inhomogeneity of the electric field resulting from the defects in the insulation structure, intrusions, etc. ($\beta = E_{max}/E_{av}$ in the case of polymers it is assumed or calculated in [4] within the limits $3 < \beta < 5$),

η -the coefficient of inhomogeneity of the electic field from electrodes (e.g. in the case of the wound electrode of a capacitor $\eta \approx 1{,}3$, in case of plane electrodes $\eta = 1$)

A,b-parameters (adopted for polymers, e.g. as: $A \approx 4*10^{-7}$ [J/V] , $b \approx 0{,}001$ [1/K]), the sign "+" w eq.(6) occurring at the tensile force, and the sign "-" at a stress compressing the material.

The use of the respective sign is consistent with the thermodynamic description of the state of the material subjected to stress under the influence of external stress, thus at increased or reduced free energy of the particles.

The values of the dissociation energy of polymer bonds were assumed as $D \approx 5{,}5 *10^{-19}$ J (i.e. about 3,4 eV).

In formula (6) doubts may be raised because of the lack of consequence in the joint notation of the effect of the analysed stresses, i.e. separation of the complex of the mechanical stress, and combining the electric effect with the thermal condition of the insulation.

For a solid insulation and macroscopically thick, with inhomogeneities in its structure, as well as fragments of increased conductivity as places of a most likely damage, the probability of failure q(t) at the time t of exploitation has been: defined by the dependence:

$$q(t) \approx 1 - e^{-\frac{dS}{0{,}482\eta v_o} z e^{\frac{0{,}83\ln 1{,}3p}{z}}} \tag{7}$$

$$z = \left\{ \ln \frac{1 - \frac{1}{g}}{1 - \dfrac{\frac{\beta}{x}\left(\frac{1}{D} A e^{-bT}\eta E\right)^2 \ln\varphi(x)}{\sqrt{1-2x} - \frac{1}{x}\left(\frac{\gamma\sigma}{D}\right)^2 \ln\varphi(x) - \frac{2kT}{D}\ln\frac{t}{\tau_o}}} \right\}^{0{,}82} \tag{8}$$

$$g = \frac{\varepsilon_1}{\varepsilon_2}\sqrt{\frac{1 + tg^2\delta_1}{1 + tg^2\delta_2}} \tag{9}$$

where: d -thickness of insulation,

S -surface of insulation,

ν_o-mean volume of the material with single inhomogeneity (adopted in [4] for polymer as being of the order 2÷ $*10^{-7}$ m^3),

p. -the so-called averaged concentration of inhomogeneity expressed as the ratio of the inhomogeneity volume to the cube of average distance between the inhomogeneities (in [4] - of order 0,15)

ε_1, ε_2-dielectric constatnt for inhomogeneity and average for insulation,

tg δ_1, tg δ_2 -coefficients of dielectric losses for the zone of inhomogeneity and the insulation, respectively.

For polymer : g≈5 is assumed. The analyses of selected insulation systems with the insulation volume of the order of some dm^3, at the intensity level of the electric field of the order 2 V/μ m for q(t) ≈0,99, and the other material constants as above, have led to the estimations of durability over a period of several years, which in the opinion of the author of the present study are too optimistic.

2. INCOMPLETE AND INCONSISTENT STATE OF PROCEDURES AND THE CONDITIONS OF AGEING INVESTIGATIONS SUITABLE FOR THE ESTIMATION OF SYNERGISM

Currently state of knowledge will be presented.

When it is suggested that the phenomena of interaction, the compensation law and the scale coefficient should be taken into consideration in the models, the specific character of the interaction of many kinds of stresses has also other implications for the research procedures which may concern the methods. For example, there are investigated the possibility and the adequacy of modelling and predicting the life time of the insulation with simultaneously or sequentially acting stresses.

An example of such an analytical approach may be the estimation of synergism of thermal and electrical stresses of a mica-resin insulation of electric machines in the studies by Kako and co-workers [5, page 72] with known, single-stress sequential effects of stresses. Assuming the cumulative character of degradation, an extremaly short but alternating operation of each stress is presumed, and the degree of degradation (expressed as a decrease of electric strength) is expressed as the product of the degradation rate (in accordance with the kinetics of chemical reactions for any stress) and the time of its operation. The results of the above reasoning are shown in formula (10) - preserving the initial form of the dependence given by the authors, who do not provide any explanation for the doubts concerning the correctness of the physical dimensions of the particular quantities of their notation - form which there results a distinct decrease of the value of the life time LtV at both simultaneously acting stresses:

$$L_{tV} = \frac{1}{(n+1)K_t} \ln[1 + L_V(n+1)K_t] \qquad (10)$$

where: K_t=K(T)-Arrhenius reaction rate constant,

L_V -life time only at electric ageing,

n -parameter (exponent index in so-called inverse-power type model of electric ageing).

Conclusions, adequate to the above study, result from reasoning based on similar premises and from experiments reported in the studies [6,7,8,9,10]: many experiments show a more pessimistic value of the life time from exploitation stresses - close to the rated values - than the value predicted from the models, which means that the phenomena of multifactor synergism have not beeen accurately presented.

For example, Kulakovskij and Samorodov [9], starting from the estimation of the degree of the insulation degradation - at the operation of a single stress - measured by its relative breakdown electric strength (for the time t=0 the electric strength E(0)=1) having the form:

$$E(\tau) = (1 - \frac{\tau}{t})^{\frac{1}{n}} \qquad (11)$$

where: t -durability, equivalent to attaining zero value of the electric strength, anlaysed the results of ageing mica-resin insulation, subjected to electrical and mechanical stresses.

These authors proposed some effective forms of multistress life models by simply summing up the decrease in the value of electric strength at simultaneous operation of the stresses ($\Delta E = \Sigma [E_o - E_i(\tau)]$), obtaining, among others, for N stresses and zero value of the final electric strength , the dependence:

$$N - \sum_{i=1}^{N} (1 - \frac{\tau}{t_i})^{\frac{1}{n_i}} = 1 \tag{12}$$

which in the case of two operating stresses gives the resultatant implicit notation of durability t_Σ as:

$$(1 - \frac{t_\Sigma}{t_1})^{\frac{1}{n_1}} + (1 - \frac{t_\Sigma}{t_2})^{\frac{1}{n_2}} = 1 \tag{13}$$

When the index exponents are equal, n1=n2=1 formula (13) leads to very simple dependence:

$$\frac{1}{t_\Sigma} = \frac{1}{t_1} + \frac{1}{t_2} \tag{14}$$

which is approximately equivalent to summing up the rate of the insulation degradation from the particular stresses, at the assumption that they are inversely proportional with respect to the corresponding single-factor durabilities:

The above approach has been questioned in [9], and this criticism has been confirmed by considerable errors (up to 300%) in the use of the relations (14) to verify the experimental results. And will be suggested taking into consideration the synergism of stresses in the life model successively through: summation of the rate of changes in the electric strength from each factor (stress) and introduction of the "weight" coefficients α_i - as a measure of synergism. They recommended also experimental determination of the values of these coefficients for practical analyses. From the general form of the cumulative degradation rate, according to :

$$\frac{dE}{d\tau} = -\sum_{i=1}^{N} [\frac{\alpha_i E_o^{n_i}}{n_i t_i} E^{1-n_i} + (1-\alpha_i)\frac{E_o}{n_i t_i}(1 - \frac{\tau}{t_i})^{\frac{1-n_i}{n_i}}] \tag{15}$$

the minimal joint durability (at $\alpha_i=1$) is derived from the dependence:

$$t_{min} = \int_0^{E_o} \frac{dE}{\sum_{i=1}^{N} \frac{E_o^{n_i} E^{1-n_i}}{n_i t_i}} \tag{16}$$

The above mentioned analyses are visualized in Fig.2. Following the suggestion of the authors, for the purpose of the evaluation of the experimental results, it has been assumed, for the sake of simplicity, that n1=2 ,n2=4, t1=t2=t, which at the above assumptions, in a two-factor stress yields the analytical form of ageing as:

$$\frac{\tau}{t} = 1 - (\frac{E}{E_o})^2 - 0{,}5\ln \frac{3}{1 + 2\left(\frac{E}{E_o}\right)^2} \tag{17}$$

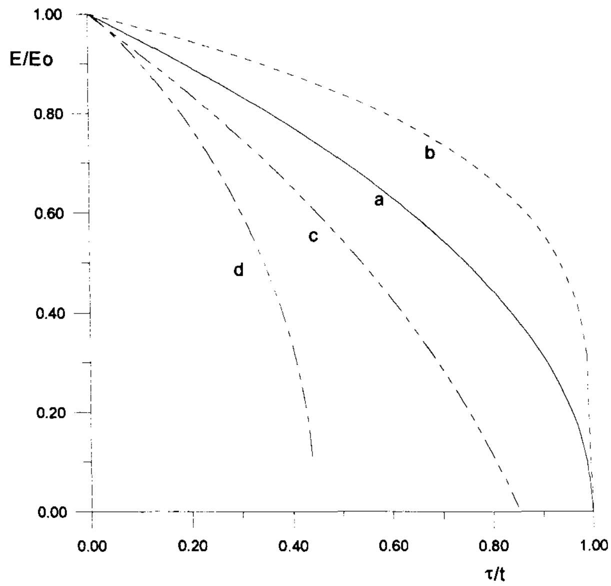

Fig.2 : The relative changes of dielectric strength of insulation during ageing testing τ :
a, b) for single stress if n1=2 and n2=4;
c) for two stresses acting simultaneously,
d) for two stresses acting simultaneously, calculated for maximal value of interaction coefficient as in eq.(17).

３. IEC PROPOSALS

In the light of the above presented illustrative consequences resulting from ambiguous interpretations of the functional notation of the intensity of insulation degradation for multistress ageing, it appears necessary to unify the investigation procedures of ageing as well as the procedures of estimating reliable life models. Establishing of the methods of ageing investigations should be preceded by a preliminary analysis of the state of knowledge in this field of research, proposal of a preliminary form of the functional dependences of the life model - at the presumed scale of the interaction of the stresses on the sample properties. As there exist no respective general recommendations and instructions, it appears justified to carry out pilot tests. In the IEC instructions - publ. 792 [2], there can be found methodical directions for constructing a plan of multistress ageing tests, as shown in the diagram in Fig.3.

The choice of the methods of ageing investigations depends, first of all, on the evaluation of the nominal operating conditions of the insulating systems, i.e. the number and the sequence of stresses. Depending on the evaluation - as far as the present state of knowledge allows it - of the possible interaction of stresses on the properties of an electrical devices or insulation systems, the investigations should be carried out in single or multistress tests.

Single stress examinations are preferred only in situations where the absence of synergism has been definitely stated. However, a non-linear, non-additive effect of several stresses can more often be suspected - at the assumption of both the accelerating and the retarding character of degradation - and then it is necessary to carry out multistress investigations rather at simultaneous than at sequential action of stresses. A broader, cognitive result of an ageing examination is attained when sequential and simultaneous multistress tests are carried out, as it is the case with assumed multistress interactions of indirect type.

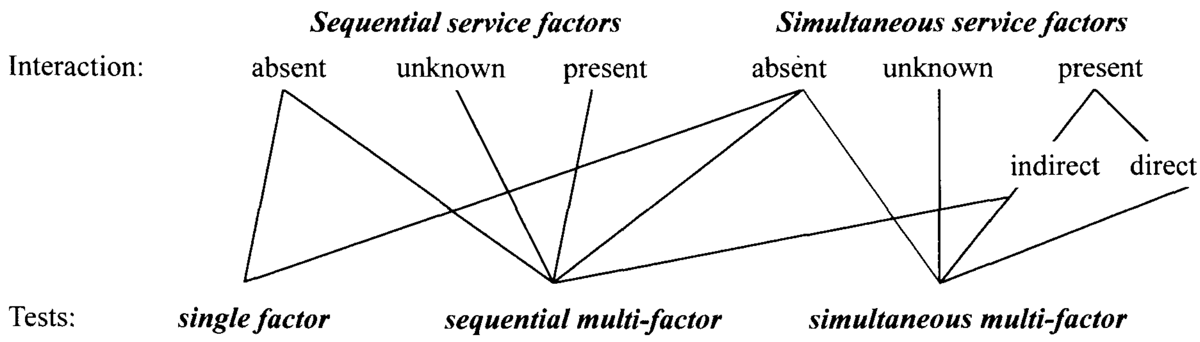

Fig.3 : Alternative ageing procedures proposed by IEC publ.792-1/85 [2].

The direct character of interaction in the process of thermal ageing can be observed, for example, in such an interaction of the electric field which causes increasing loss of active power in the insulation, and in this way also an increase of temperature. This phenomenon can be observed in a wide range of insulation systems, where the loss coefficient tg δ of the examined object is a function of both (thermal and electrical) stresses. Metallized capacitors are here a special example. From this point of view they represent an object in which the exploitation thermal-electric stresses cannot be regarded as sequential, and they require - in accordance with

Fig.3 - multistress investigations of simultaneous stresses. It should be noted - which is not dissused in the above mentioned standard - that in such a case, on account of the inhomogenous temperature field, e.g. within the volume of the capacitor (but in other objects, as well) the intensity of thermal ageing will differ at places, and in this situation the test conditions should be defined either by the ambient temperature, or- for the purpose of study- by the maximal starting temperature in the insulation, if it is known. This problem can also find a practical solution, such as it takes place in the endurance test of capacitors of various types, in which the starting thermal conditions of the test are defined by the maximal temperature of the capacitor casing after a period (e.g. 24 hours) of thermal stabilisation. The thermal ageing conditions of an object with local sources of heat will depend on the intensity of heat exchange with the environment - rather constant during the test, hence the principles of the solution of appropriate cooling methods during the tests will be welcomed in the above instructions. It appears that for objects of small overall dimensions, e.g. small power capacitors the values of heat transfer coefficient of the order of 20 W/m^2K will appriopriate, and for objects of power capacitor type - the values of about 10 W/m^2K. This coefficient may be of vital importance for comparative evaluations of the investigation results of accelerated ageing.

According to [2], the direct or/and indirect interaction of thermal-electrical stresses may take place at the exposition of the ionizing character of ageing when intensive partial discharges are the source of the occurence and the degradating reactions of chemically active particles and ions - depending on their life time. Additional interaction of mechanical stresses at thermal ageing to local temperature increase (also to reduction of the indices of mechanical strength), and such a type of interaction is thought to be an indirect one. The unquestionable advantages of the above mentioned standard are : pointing out the necessity of statistical analyses of the investigation results, carring observations on numerous samples, the need to verify the investigation results in an additional test as a final one, confirmation of tests until at least half of the samples (examined together) have been damaged. It seems also that the recommended percentage of damages in a single test should be at a level of above 60%, and the number and length of the cycles should be optimal for the set purpose of the investigations. In the procedure of choosing the criteria for the evaluation of the behaviour of the examined samples, the so-called end-point criteria,there are included also,in the above standard, the parametric criteria for the quality characteristic of the samples determined by non-destructive methods.

Insulation systems and electrical devices are aged in functional tests using rather alternating voltages with the values order 115 - 200% of rated conditions (rarely above this threshold), at electric gradient from few to 200V/μ m., at temperatures - depending on the class of insulation - up to 270℃, with mechanical stresses - shakers, strokes, overloading - up to 20g, with gamma-radiation of the order 0,015-0,046 Mrad/h, and also under voltages of higher frequencies (some tens of kHz), as well as non-sinusoidal pulse voltages. There are also be found cases when ageing is accomplished with both direct and alternating voltages in order to estimate the effect of the voltage type on durability.

An alternating electric field is a self - contained source of cyclic mechanical stress of insulation, in the devices or installations, and e.g. in the case of capacitors it is responsible for the vibration of electrodes.

Multistress tests of accelerated ageing investigations may be carried out as sequential or simultaneous - with the possible exposition of the effects of the interaction of stresses.

The duration of ageing tests in certain cases is as high as some thousands of hours. Depending on the type of the ageing tests, as well as the range of investigations - the sample lab population in the test is from 5 to 200 speciments.

4. SELECTED LIFE MODELS OF INSULATION SYSTEMS

Below, for the purpose of demonstrating the most representative forms of the life models containing parameters describing the synergism of stresses for various insulation systems, there have been selected the respective functional dependiencies of the life models; if they have not been especially specified in the group of electric stresses, they are valid for sinusoidal voltages of mains frequency. Where it was possible, the values of the estimated ageing parameters have also been given.

<u>* The model of Wasilenko</u> [3] - for polymer insulation, as a example of a thermofluctuation model:

$$t = \frac{\frac{h}{kT} e^{\left(\frac{2W - kT - \alpha U}{kT}\right)}}{e^{\frac{W - kT}{kT}} - e^{\frac{W - \alpha U}{kT}}} \tag{18}$$

where: W- activation energy (from the measurements for ethylene W=0,95÷1,20 eV), $h=6,63*10^{-34}$ Js (4,14 10^{-15} eVs) k=1,38 10^{-23} J/K (0,86 10^{-4} eV/K) - Planck and Boltzmann constants,

α - coefficient of entropy, from the measurements 0,012÷0,021 eV/kV,

T- absolute temparature [K].

From the dependence (18) there can be defined the so-called threshold voltage as: $U_o = kT/\alpha$, below wich the stressed insulation demonstrates infinitely great durability.

The practical demonstration of the value of the threshold voltage is important for the procedures of ageing investigations, for the effectiveness of the search for the life model insulation, particularly for stresses close to rated ones, thus for those near the voltage threshold. A proposal of an empirical determination of the threshold voltage through the measurement of voltage breakdown indentified with the threshold voltage, for a polymer insulation has been given by Wasilenko [11]. The estimated value of the threshold voltage U_0[kV] for some materials (PE, XLPE), described by dependence (19), is also confronted with many independent sources with satisfactory agreement of the values:

$$U_0 = 2{,}14\, \phi^{-0{,}213 + 0{,}03 \ln d}\, d^{0{,}66} \tag{19}$$

where: 0,02mm$\leq$d$\leq$35mm-insulation thickness,

ϕ - diameter of the break-up channel [mm].

The results of comparative investigations lead to a practical conclusion: calculation of the characteristic and functional value of the threshold voltage for a polymer insulation should be made for the diameter of the break channel not smaller than ϕ=0,01 mm. For example, for the insulation thickness 0,18 mm it has been obtained U_0=1,46 kV for PE, and for XLPE with the thickness 1,5 mm - the value of U_0=7,9 kV.

<u>* The models of Cygan and co-workers</u> [14], for polypropylene foil, determined in ageing investigations at direct voltage in the range of stresses UDC=11÷15,6 kV - direct current - (for a sample of the thickness 25,4 μm, E=433÷630V/μm) and temperatures θ : 23÷90℃ :

$$t = 5{,}89\, 10^{-9}\, e^{0{,}85\, U + \frac{12990}{\vartheta + 273} - 599 \frac{U}{\vartheta + 273}} \tag{20}$$

where: U[kV], t[s]

The above authors reported also the results of experiments conduced at alternating voltage in the voltage range 2÷5kV, obtaining significantly different (lower) values of durability from those obtained under direct voltage stress, which has been confirmed by the investigation results of the next, presented model.

* The models of Hemalatha i Ramu [15] for polypropylene foil, saturated with oil, of the total thickness 25,4 μ m (including the results for mica-resin insulation, too) estimated from investigations at alternating voltage as an example of the model Eyring and Fallou type and for comaprison with the results of Cygan; for the stresses: temperature θ 50 ÷ 90℃, electrical gradient E=70÷90 V/μ m:

$$t = 2{,}7\,10^{-6}\, e^{0{,}0806E + \frac{8151}{\vartheta+273} - 58\frac{E}{\vartheta+273}} \qquad (21)$$

where: E [V/μ m]

* The model of Bielenki [16], as a simplified form of the thermofluctuation model, interesting so far that it has been intended for high voltage capacitors in the stress range: temperature 75÷125℃, direct electric gradient 100÷175 V/μ m; for 100 samples of capacitors in one ageing test.

$$t = t_o\, e^{\frac{W - 0{,}23\frac{U}{U_o}}{kT}} \qquad (22)$$

in the range of the test the changes of the activation energy W from 0,48 to 1,9 eV has been observed, while to corresponds to durability determined for the reference voltage U_o.

* The models of The "Bologna School"- of Simoni, Montanari, Cacciari, Mazzanti, Lefebre - on the basic and in a form summarizing many years long investigations and analyses from the studies [17,18,19,20]; describing the durability of insulation systems, verified experimentally for polyethylene, ethylene-propylene rubber and polypropylene.

Below there will be presented selected forms of notation of multi-parameter, two-stress life models of insulation for electric - thermal stresses E and T - using the values of the reference durability for the life time denoted as to at room temperature - presented as universal proposals; for materials with and without voltage-thermal thresholds. The thermal stress is expresses here as the difference of the inverse of the temperature θ o[K], below which the thermal degradation of the insulation is usually neglected and often it is assumed as the room temperature θ a=293K and the stress temperature θ [K], according to the dependence T=1/θ o -1/θ . E denotes the electric gradient

$$t = t_0 \frac{e^{-h\bar{E} - BT + bT\bar{E}}}{\left(\frac{\bar{E}}{\bar{E}_{to}} + \frac{T}{T_{to}} - \frac{k\bar{E}T}{\bar{E}_{to}T_{to}} - 1\right)^{\beta}} \qquad (23)$$

where: Ë=E-E_o, E_o -the value of the electric gradient , below which electric ageing can be neglected at the threshold temperature - T_{to},

Eto- threshold value of the electric gradient at room temperature - θ a.

$$\beta = \beta_0\left[\left(\frac{\bar{E} - \bar{E}_{to}}{\bar{E}_{to}}\right)^2 + \left(\frac{T - T_{to}}{T_{to}}\right)^2\right] \qquad (24)$$

As a result of the parameter estimation of the above disscused life models, obtained from the results of experimental investigations within the range of alternating field intensities with E=2÷20 V/μ m and the temperatures θ =20÷180℃, the authors have obtained the following parameters for polyethylene: B=9000, b=400, t_o=107 hours,

E_{to}=11V/μ m,E_o=2V/μ m,T_{to}=7,31*10^{-4}(which corresponds to the temperature θ_{to}=100℃), h=0,58, k=0,5, β o=0,8.

On the basis of the presented results of estimation of the life models parameters, in Figs. 4,5 there are given the graphs of the values of selected quantities in the respective stress intervals. The value of the exponent superscript of the denominator of the dependence (24), as it is shown in the graph in Fig.5, is determined, first of all, by the value of the field intensity. An analysis of durability changes according to dependence (23) is possible within a limited range of such stresses for which the value of the denominator of this expression (without that component of exponent) is positive, which is demonstrated, among others, in Fig.5

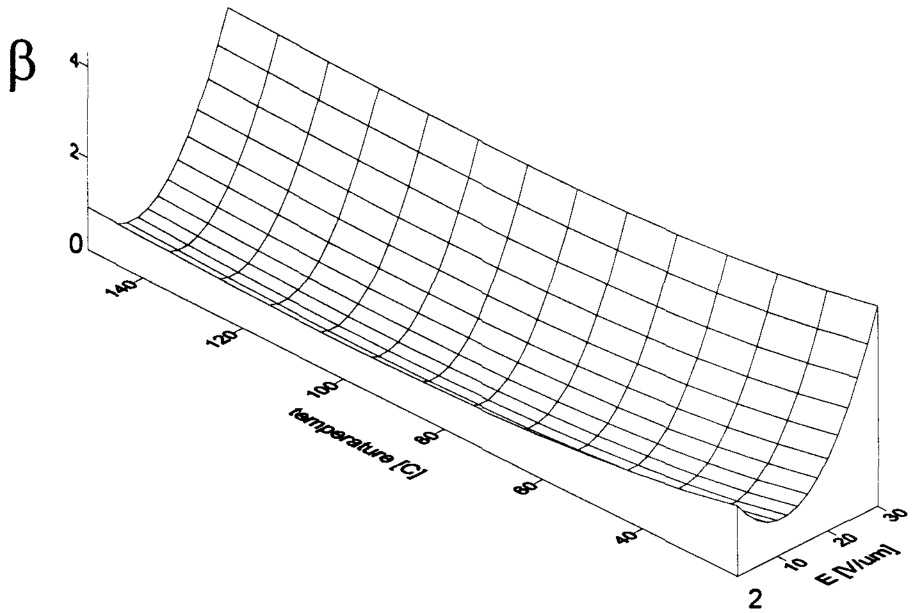

Fig.4 : The value of the parameter β calculated from (24), for polyethylene.

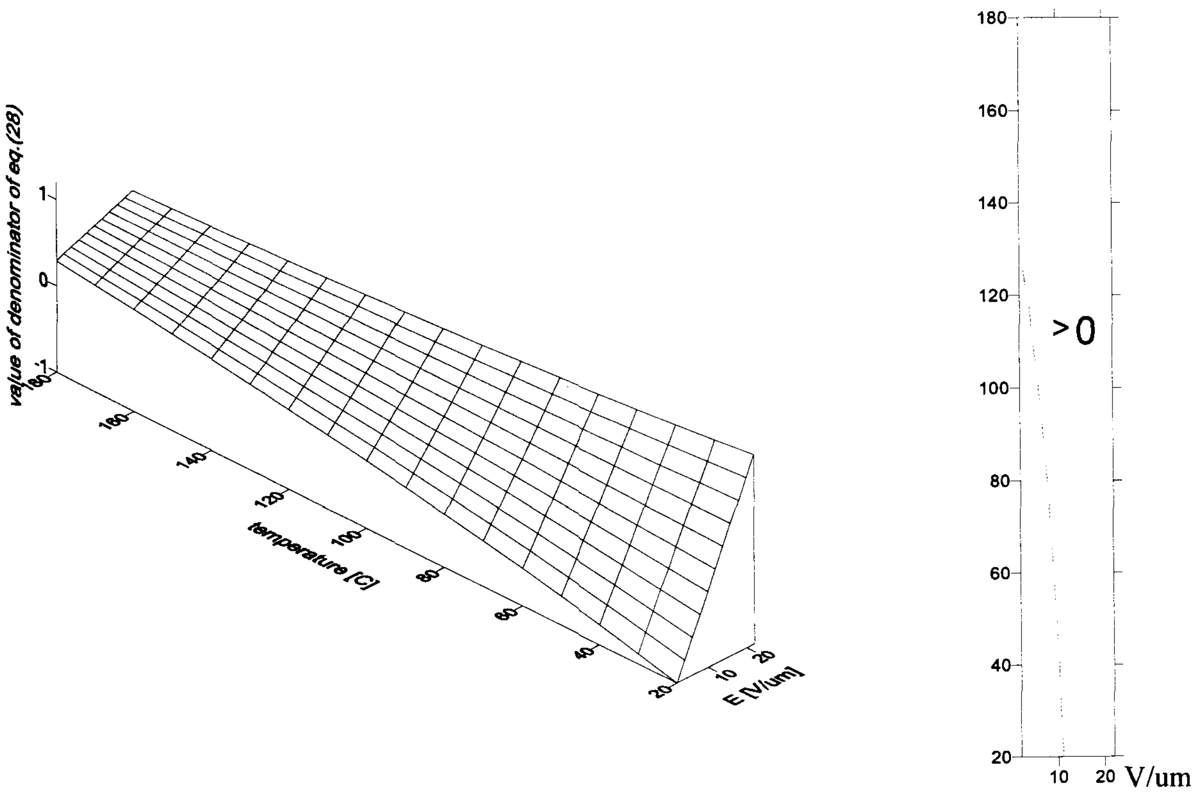

Fig.5 : The value of denominator of Eq. (23) without taking into account the parameter (and the line of its zero value at the investigation conditions.

The last inconvenience is fairly important limitation in the practical application of formula, as well as the other dependences.

The model of Srinivas and Ramu [21] - the three stress model proposed for mica-resin insulation of generators and aided with graphical results of investigations for: thermal stresses θ =155 ÷ 230℃, mechanical from 0 to 66 N/cm^2 with vibration 120÷4130Hz and electrical stress 20÷26kV. The rated work parameters of this insulation are: voltageU= 6 kV, temperature 155 ℃ (428K) and mechanical stress S=0,55 N/cm^2

$$t = 2{,}16\,10^5 \left[\frac{E}{E_0}\right]^{-6{,}5+0{,}05\,S} \left[\frac{S}{S_0}\right]^{-3{,}5} e^{\frac{4000}{\vartheta+273}+\frac{2{,}07}{ln\frac{E}{E_o}}} \tag{25}$$

where: t- durability [h], and E, θ ,S- electrical, thermal and mechanical stress, respectively, and the corresponding reference values (with index "0"). In the investigation conditions there have been observed changes in the value of the estimated index exponent connecting with voltage factor in the range from 5,5 to 8,4 with relatively wide confidence intervals.

The above model has been verified by the authors in a experiment for some values of stresses - however, not for the rated ones - with respect to the durability value determined analytically from the dependence (25), obtaining about 50% relative error. It has been agreed, however that the above dependence is the most representative for modelling the life time of machines even in case of three stresses.

* The model of Pandey and Lin [22] - as an example of a classical notation of an analytical two-stress model for paper insulation, 254 μ m thick, aged at temperatures θ =50÷100℃, at alternating voltage U=600÷900V, i.e. at field gradient of about E=2,35÷3,5V/ μ m. To derive the model there has been used the data base with the criterion of a parametric damage of the insulation, i.e. the times of attaining 10% of the starting value of resistance.

$$t = 0{,}118\, e^{\frac{2600-72{,}7\ E}{\vartheta+273}} \tag{26}$$

where: t [h]

*The model of Siwik [23] - for paper-oil capacitors 8 μ F/500V, determined for the alternating voltage range U: 575÷675V (20÷25V/ μ m) and ambient temperatures θ a: 60÷80℃, in the mode of multicriterion estimation from the data base, containing the times till complete damages and changes in the capacity values and in the loss coefficients.

$$t = 0{,}938\,10^{10} e^{-0{,}013\ U-0{,}051\ \vartheta_{max}-0{,}506\,10^{-4} U\ \vartheta_{max}} \tag{27}$$

where: θ max= θ $_a$+10^{-7} U^{3,055} is value of maximal temperature inside capacitor [℃].

5. SUMMARY

Basing on the above results, the components describing the synergism of stresses has been isolated from the models - in the Table 1, and its notation - at first - unified to a form closer to various form and that of the thermofluctuation model, too. However, while taking into consideration the variety of forms in the functional notation of the life models, the scarity of information about the conditions of some investigations of the insulation systems, it has been decided yet to display two alternative and equivalent components with voltage value and/or electric gradient. The authors are aware of the fact, that in many cases the real value of electric gradient in the insulation may differ from the calculated. The values of synergism components calculated in that way depend on the stress conditions, hence in Table 1 there are given their values for averaged conditions of the performed ageing investigations.

The calculated values of electric-thermal synergism, listed in Table 1, do not show any considerable divergences in the group of morphologically similar insulation systems, at similar type and scale of voltage stresses and in a fairly wide temperature range.

Accordingly, it appears possible as well as justified to use the values listed in Table 1 when planning experiments on multistress ageing of insulation systems.

The results of the performed analyses do not ultimately decide whether within wide ranges of stresses the measure of the stress synergism is a constant. Other examples of ageing investigations of insulations indicate rather that the life models are physically adequate for limited values of stresses. The dependence of the values of the ageing parameters of life models on the stressing quantities, observed in many investigations and indicating a change in the ageing mechanism, remains the basic and not yet solved problem of the estimation of a reliable utilization of models - estimated from tests of accelerated ageing - in stress areas close to the rated ones.

In practice, with the lack of knowledge of the analytical or not experimentally confirmed interactions, the permissible estimation of lifetime values is the estimation of pessimistic durability models.

Most ageing investigations are carried out on small samples - not real objects, and here, in the process of modelling there appears another important problem - to transfer thus elaborated models to the scale of a real technical object, whose prediction of behaviour is the object of our interest. Consideration of the stochastic character of the ageing phenomena, analysis of the number of weak points in the insulation are the more important for the modelling process of ageing, the greater are the overall dimensions of the electric devices, for which the durability diagnosis is made, when compared with the examined sample of the insulation system.

Estimation of adequate, multistress ageing parameters of the life model with consideration given to the estimation of the interaction of stresses requires necessarily that the ageing tests are carried out on large populations (of the order of 50 pieces) with their simultaneous, not sequential exposure to stress. The object of the investigations should correspond as closely as possible to the appliance for which the estimation of the life model is being made.

Above observation indicates the necessity to apply additional coefficients of the life models transformation in the estimation of durability - the synergism .

Table 1

Forms of exponential components, isolated from two-stress life models of selected insulation systems describing the synergism of electric-thermal ageing (T= θ +273[K]).

Material	Kind of voltage	Voltage value U [kV]	Electric gradient E [V/μm]	Temp. ϑ [°C]	Component of synergism with E	Component of synergism with U	From:
Polethylene	AC	12,5 ÷ 24		20		$e^{-190\frac{U}{T}}$	eq.(18) at α_{av}=0,0165 eV/kV
Polypropylene	DC	11 ÷ 16	430÷630	25÷90	$e^{-15\frac{E}{T}}$	$e^{-600\frac{U}{T}}$	eq. (20)
Polypropylene/ oil	AC 50Hz	1,8 ÷ 2,3	70÷90	50÷90	$e^{-60\frac{E}{T}}$	$e^{-2287\frac{U}{T}}$	eq. (21)
Polyethylene	AC 50Hz		2÷20	20÷180	$e^{90\frac{E}{T}}$		eq. (23)
Paper	AC 50Hz	0,6 ÷ 0,9	1,5÷3,5	60÷80	$e^{-70\frac{E}{T}}$	$e^{-280\frac{U}{T}}$	eq. (26)
Paper/mineral Oil	AC 50Hz	0,57÷0,67	20 ÷25	80÷110	$e^{-80\frac{E}{T}}$	$e^{-2700\frac{U}{T}}$	eq. (27)

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